A Rotating Inconel Band Target for Pion Production at a Neutrino Factory, using Study II Parameters[1]

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Abstract

A conceptual design is presented for a high power pion production target, based on a rotating band of inconel alloy 718, that is intended to provide a back-up targetry option for the Neutrino Factory Study II. The target band has a 2.5 m radius and has an I-beam cross section that is 6 cm high and with a 0.6 cm thick webbing. The pion capture scenario and proton beam parameters are as specified for the Study II base-line targetry option, i.e. capture into a 20 Tesla tapered solenoidal channel with proton beam fills at 2.5 Hz containing 6 short bunches, each spaced by 20 milliseconds, of 1.67×10^{13} 24 GeV protons. The target is continuously rotated at 1 m/s to carry heat away from the production region and through a water cooling tank. The mechanical layout and cooling setup are described and results are presented from realistic MARS Monte Carlo computer simulations of the pion yield and energy deposition in the target and from ANSYS finite element calculations for the corresponding shock heating stresses.

1 Introduction and Overview

The design of a pion production target for the Study II [1] neutrino factory parameters is challenging because of the combination of high average power and large instantaneous energy depositions from the 24 GeV pulsed proton beam, the geometric constraints from the capture solenoid surrounding the target, and the desire to maximize the pion yield for 24 GeV protons through use of thin targets constructed from elements with high or medium atomic numbers. As a back-up scenario to the base-line mercury jet target design, this note presents

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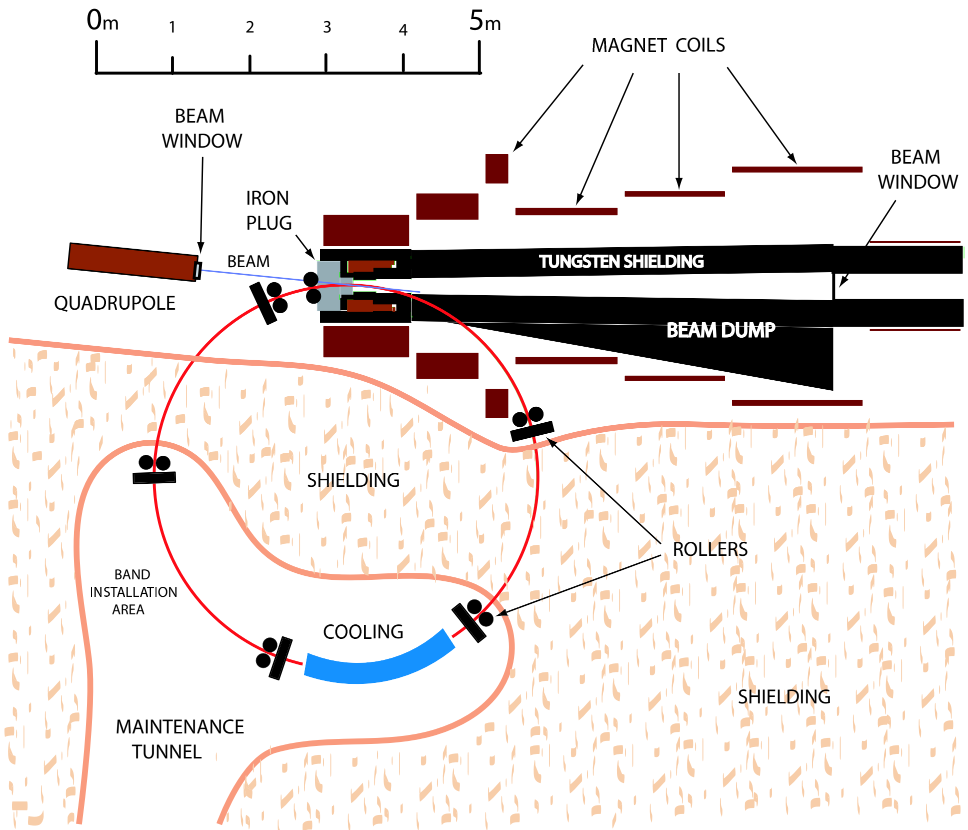

Figure 1: A conceptual illustration of the targetry setup.

a solid-target option that is based around an Inconel Alloy 718 target in a rotating band geometry. An abbreviated and less complete version of this note is included as an appendix in the study II report [1].

A plan view of the targetry setup for the band target option is shown in figure 1. A 2.5 meter radius circular target band threads through a solenoidal magnetic capture channel to tangentially intercept the proton beam. The circulating band is cooled by passage through a water tank located in a separate shielded maintenance enclosure. Similar conceptual designs for rotating band targets have been presented previously [2, 3, 4] for use at both muon colliders and neutrino factories, and a paper is in preparation [5] that considers the options for modifying, for use with muon collider beam parameters, the band target design discussed here.

The sections in this note discuss, in order: the properties of inconel 718 and the specifications of the inconel band and the incident proton beam, the drive and support rollers for the target band, considerations for operating the target region in an air environment, required modifications to the pion capture

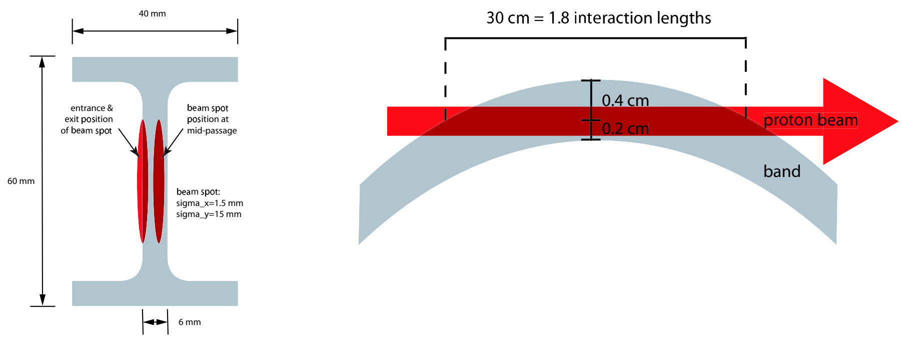

Figure 2: Passage of the proton beam through the target band, shown in cross-sectional (left) and plan (right) views. The horizontal position of the beam spot in the band webbing varies along the interaction region due to the curvature of the band. The plan view shown in the right plot has a 10:1 vertical:horizontal aspect ratio.

and decay channel in order to incorporate the rotating band, cooling of the band in a water tank, radiation damage and the replacement scheme for the target band, MARS Monte Carlo simulations of pion yield and the beam energy deposition distribution, beam-induced shock heating stresses on the target band and, finally, overall conclusions on the rotating inconel band target scenario for pion production with the proton beam specifications for the Study II Neutrino Factory.

2 The Inconel Target Band and Incident Proton Beam

The target band material is inconel 718 [6], a niobium-modified nickel-chromium-iron superalloy that was developed for aerospace applications. It is also used in high radiation environments such as the core internals of light water nuclear reactors, due to its high strength, outstanding weldability, resistance to creep-rupture and resistance to corrosion from air and water. As examples of applications at accelerators, it has been used for high intensity proton beam windows and as the water containment material for proton beam degraders. Inconel 718 was proposed for beam windows and for cladding the tungsten target elements in the 170 MW proton beam at the (now defunct) Accelerator Tritium Production (ATP) project and is the back-up candidate (behind 316LN stainless steel) for the construction of Spallation Neutron Source (SNS) target components.

The elemental composition of inconel alloy 718 that was used for pion yield calculations is [6] (with percentage by weight then molar fraction in the brackets): Ni (54.3%, 0.537), Cr (19.0%, 0.212), Fe (17.0%, 0.177), Nb (5.1%, 0.032), Mo (3.1%, 0.019), Ti (0.9%, 0.011), Al (0.6%, 0.013). Further relevant properties of inconel 718 are summarized in table 2.

The inconel target band has a radius of 2.5 meters and a 15.7 m circumference. Its dimensions and orientation relative to the proton beam are shown in figure 2. The band has an I-beam cross section for enhanced stiffness. The proton beam enters the center of the target band webbing at a glancing angle and the beam center traverses 1.81 interaction lengths of target material before the protons that haven't interacted exit the target due to the curvature of the band.

The proton pulse structure and bunch charges were assumed to be identical to the base-line scenario [1] for a mercury jet target, i.e. proton beam fills at 2.5 Hz containing 6 short bunches, each spaced by 20 milliseconds, of 1.67×10^{13} 24 GeV protons. For the band target design discussed here, the proton beam is incident at a horizontal angle of 100 milliradians to the magnetic field direction and is focused to an elliptical beam spot at the target interaction region with assumed gaussian profiles in both transverse dimensions and with r.m.s. spot sizes of 1.5 mm (horizontal) and 15 mm (vertical).

The dimensions of the band webbing and proton beam spot were chosen to approximately maximize the pion yield while keeping the density of energy depositions in the target to an acceptably low level. The general requirements for yield are that the proton path length through the target material should be [7, 8] approximately 1.5–2 nuclear interaction lengths, and that the band should be thin enough to allow most of the pions to escape the target. Tilting targets by approximately 100 milliradians with respect to the capture solenoid has generally also been found [7, 8] to slightly increase the pion yield. On the other hand, the elliptical beam spot was chosen solely to reduce the beam-induced stress by spreading out the beam energy deposition within the target.

Table 2 presents the parameter specifications that have been assumed for the inconel target band and the incident proton beam.

Table 1: Tabulation of some relevant properties of inconel 718.

ave. atomic number, Z	27.9
ave. atomic weight, A	59.6
density (ρ)	8.19 g.cm^{-3}
interaction length (λ)	16.6 cm
radiation length (X_0)	1.55 cm
melting point	1298 °C
heat capacity (C)	0.435 J.K^{-1}.g^{-1}
thermal conductivity	11.4 W.m^{-1}K^{-1}
electrical conductivity	0.8 MS.m^{-1}
expansion coefficient (α)	1.3×10^{-5}/K
elastic modulus (E)	2.3×10^{11} N/m^2
0.2% yield strength (annealed)	740 MPa
0.2% yield str. (precipitation hardened)	1100 MPa

Table 2: Specifications of the inconel target band and assumed proton beam parameters.

target band radius	2.5 m
band thickness	6 mm
band webbing height	60 mm
full width of band flanges	40 mm
beam path length in band	30 cm
proton interaction lengths (λ)	1.81
weight of band	98.8 kg
band rotation velocity	1 m/s
proton energy	24 GeV
protons/bunch	1.7×10^{13}
bunches/fill	6
time between extracted bunches	20 ms
repetition rate for fills	2.5 Hz
horizontal beam-channel angle (α)	100 mrad
rms beam spot size at target (horizontal)	1.5 mm
rms beam spot size at target (vertical)	15.0 mm

3 Target Band Drive and Support Mechanism

The target band rotates at 1 m/s with a rotation sense away from the proton beam direction. The rotation speed was chosen largely from considerations of beam-induced stresses. For the 2.5 Hz repetition rate between proton fills, the target advances by 40 cm between successive fills. Hence, each beam fill is presented with a fresh 30 cm chord of target band and the fills are rendered essentially independent from the point of view of local target heating and stresses. Nearly the opposite situation applies for the proton bunch microstructure within each fill: the 20 millisecond interval between successive bunches corresponds to a target advance of only 2 centimeters and the energy depositions from the 6 bunches within each fill are largely superimposed. This level of energy pile-up was considered acceptable since the most damaging transient tensile stresses are expected to die out on a time scale very much shorter than the bunch spacing – see section 9.

The band is guided and driven by several sets of rollers located around its circumference, as is shown in figure 1. The tightest position tolerances on the rollers are the precisions of 1 mm or better required for the rollers defining the band's horizontal position at interaction with the beam.

It has been roughly estimated that only a few hundred watts of drive power will be required to overcome the eddy current forces from the band entering and exiting the 20 Tesla solenoid. The eddy current power is relatively low for this particular realization of the rotating band target geometry because of (i) the low electrical conductivity of inconel 718 (only 1.4% that of copper – the eddy current power is linear in this parameter) and (ii) the band rotation velocity is only 1 m/s (the eddy current power is quadratic in the velocity). The motive power will be applied from the rollers within the maintenance tunnel, where the radiation environment is less severe and maintenance is easier.

Following the design of the BNL g-minus-2 target [9], the roller assemblies will all incorporate self-lubricating graphalloy [10] bushings. These commercially available bushings are manufactured from molded graphite impregnated with metal and, in contrast to conventional lubricants, are compatible with high radiation environments.

4 Considerations for Targetry in an Air Environment

The pion production region of the target is in an air environment. This simplifies target maintenance and target band replacement by avoiding any requirement to break and re-establish seals in a high radiation environment.

The vacuum window for the proton beam-line is located immediately downstream from the final quadrupole magnet and a few meters upstream from the production region. The proton beam spot size at this beam window will be much larger than for the focused beam at the target interaction region; this minimizes the peak beam-heating stresses and radiation damage in the window and also simplifies the window cooling. The vacuum in the pion decay channel begins at a beam window located (e.g.) 6 meters downstream from the target interaction region. These distances are not expected to result in either excessive proton-air interactions upstream from the target or significant degradation of the pion yield since each meter of air corresponds to only 0.13 g/cm^2 of matter, 0.14% of an interaction length, 0.33% of a radiation length and to a minimum-ionizing energy loss of only 0.24 MeV.

Activated air and gases from the target and interaction region are continuously diluted and vented from the target hall into the outside atmosphere following the procedure adopted for the BNL g-minus-2 target [9]. Initially, a loosely airtight container around the target impedes gas transport away from the target until most short-lived radio-isotopes have decayed. (The iron plug shown in figure 1 may suffice for this purpose.) The activated air is then transported along the target hall to allow dilution by mixing with unactivated air until acceptable activation levels are reached for venting into the outside atmosphere.

5 The Pion Capture and Decay Channel

As is evident from figure 1, the pion capture channel represents only a slight variation on the the base-line mercury jet target option [1]. The magnetic field in the solenoidal capture channel is nearly identical to the base-line design. As a minor change, no requirement remains for field homogeneity upstream from the production region, so the field can be immediately tapered down from the

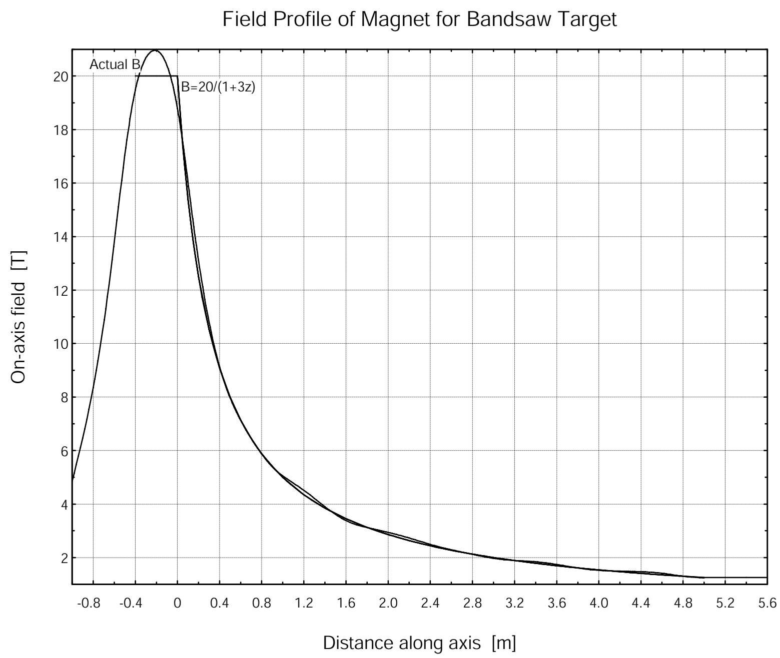

Figure 3: The on-axis magnetic field profile in the solenoidal capture channel. The plot shows, nearly superimposed, both the actual field and the "ideal" field profile that it was fitted to.

20 Tesla maximum. On the other hand, the third coil block downstream from the upstream end had to be moved outwards by approximately 10 centimeters to provide adequate space for the band to exit the channel. A modest re-optimization of the coil currents was required to restore the magnetic field map in this region to the base-line specifications. (The coil block positions and dimensions shown in figure 1 are taken directly from the computer programs used to optimize the magnet geometry and magnetic field profile.) The re-optimized magnetic field map is shown in figure 3.

The other requirement on the capture and decay channel that is additional to the base-line scenario is the provision of entry and exit ports for the target band. The design of these ports is simplified by the air environment of the pion production region. The entry port need only traverse the iron plug in the upstream end of the capture solenoid. The downstream port is more challenging since it must traverse the tungsten shielding and then pass between the solenoidal magnet coil blocks and out of the pion decay channel.

The base-line mercury jet target design scenario [1] assumes a 6-meter-long magnet cryostat enclosing the area where the band must exit. If it is considered undesirable to incorporate such an exit port into the cryostat then the magnet cryostat designers have the alternative option of breaking the cryostat longitudinally into two cryostats so the band can exit between them.

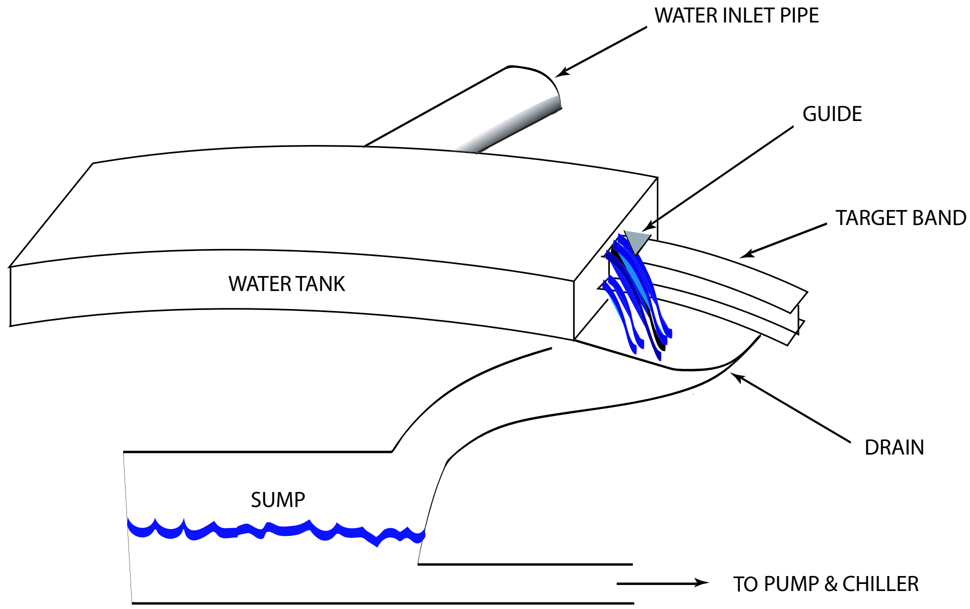

Figure 4: A conceptual illustration of the target cooling setup.

The exit port may require some cladding with, e.g., tungsten-carbide and water, to shield the magnet coils from any additional radiation load from thermal neutrons.

No detailed consideration has yet been given to the design of the beam dump. The design considerations are similar to those for the graphite target scenario considered in Neutrino Factory Study I [11]. As is clear from figure 1, the target band exit port is far enough upstream from the beam dump for it to be not a relevant factor in the beam dump design.

6 Target Cooling

The heated portion of the band rotates through a 2 meter long cooling tank whose conceptual design is shown in Fig. 4.

The water flows due to the gravitational head in a feeder tank, and the band entrance and exit ports in the ends of the tank serve as the water outlets. The flow rate can be simply adjusted by varying the water head in the feeder tank. Guides in the ports steer the water off to the side of the target band and into a drain, to then be pumped to a chiller and recirculated. The drains and structure at the ends of the tank will be covered with hoods to prevent splashing (not shown in figure 4) and, at the end where the band exits, high pressure air will blow the residual water off the wetted band as it exits the hood.

The 2 meter length of water in the cooling tank was chosen to be sufficient to obviate the need for forced convection of the cooling water: for the approximately 70 kW of heat deposited in the target band, the 0.54 square meters of immersed target band surface area corresponds to an average heat transfer rate of 13 W/cm^2, which is comfortably below the 100 W/cm^2 approximate maximum sustainable rate for nucleation cooling with standing water under favorable conditions.

The water flow rate parameters are also relatively modest. For example, an assumed 5 degree centigrade average temperature rise in the water would require an exit flow rate of about 3.3 liters per second. This flow rate could be met by a combination of 1) a 2 m/s flow velocity supplied by pressure from a 20 cm head of water and 2) an 18 cm^2 cross-sectional area in each of the 2 exit ports around the I-beam cross section of the target band.

As a desirable feature, all moving parts for the cooling loop – the pumps, chiller, valves for the feeder tank, and air compressor – can be freely located in any convenient places either inside the maintenance tunnel or entirely outside the shielding walls surrounding the target hall.

7 Radiation Damage and Target Band Replacement

The rotation of the target band has the desirable dilution effect that the rate of radiation damage on any particular section of the band material is reduced by roughly two orders of magnitude relative to a fixed target geometry since the region of maximum energy deposition from any particular proton bunch has a characteristic width on the order of the interaction length (i.e. 16.6 cm) and the 15.7 meter band circumference corresponds to 95 interaction lengths. Even so, the strength and other mechanical properties of the inconel target band might still eventually be degraded, by repeated shock heating stresses and radiation damage, to the point where the band needs to be replaced. Therefore, the target design must allow for the routine removal and replacement of the target band.

A very approximate determination of radiation damage to the target band can be obtained from the estimated fluence of particles through the target material and the rule-of-thumb that 1 displacement per atom (dpa) will be produced by a fluence 10^{21} minimum ionizing particles per square centimeter. For the Neutrino Factory Study II proton beam parameters, this predicts that a few years of operation would be required to accumulate 1 displacement per atom (dpa) of radiation damage to the inconel band material. This suggests that each target band could, in principle, last for many years because, for comparison, a 6 dpa design lifetime has been set for the 316LN steel (or inconel 718, as a back-up) target components in the SNS. Firmer estimates of the band lifetime should soon become available upon completion of the tensile strength stress tests that are currently being conducted for the SNS project on inconel 718 samples that have been irradiated to 1 dpa.

Target bands will be installed and extracted from the dedicated band maintenance area located in the maintenance tunnel (see figure 1). Remote extraction is the only viable option for heavily irradiated used bands. The band will be removed from its channel by progressively clamping and then shearing off (e.g.) 1 meter lengths and dropping them into a hot box. It is expected that, once the hot box has been locked shut and the irradiated band removed to a disposal area, radiation levels in the maintenance tunnel will have fallen to an acceptably low level to allow the immediate manual installation of the new band without the need for a cool-down period. This assumption should eventually be checked using particle tracking simulations (e.g. with MARS [12]) that can determine the level of residual radiation carried into the maintenance area by the target band and by neutrons leaking through the band ports in the shielding wall.

In what is almost the reverse procedure to band removal, the new band will be progressively welded together in situ from (e.g.) eight 1.96 meter long chords of target band that have been previously cast (or otherwise prepared) into the correct I-beam cross section and circumferential curvature. Beam-induced stresses on the welds are minimized by welding on the flanges of the I-beam rather than on the central webbing; the flanges are not directly exposed to the proton beam and will also receive much smaller energy depositions from secondary particles than the central webbing.

8 MARS Monte Carlo Simulations of Pion Yield and Beam Energy Deposition

Table 3: A summary of MARS and ANSYS predictions for pion yields, energy depositions and stresses. See text for definitions and details.

parameter	value
π^+ (π^-) yield/proton; 0.05< p <0.80 GeV/c	0.715 (0.636)
π^+ (π^-) yield/proton; 32< E_{kin} <232 MeV	0.304 (0.288)
frac. beam energy deposited in target band	~7%
total power deposition in target band	~ 70 kW
peak energy deposition/pulse	13 J/g
peak inst. temperature rise	29^oC
peak total temperature rise	< 174^oC
peak von Mises stress	1.9×10^8 N/m^2
von Mises stress, fraction of yield strength (annealed)	26%
von Mises stress, fraction of yield strength (precip. hardened)	17%

Full MARS [12] tracking and showering Monte Carlo simulations were conducted for 24 GeV protons incident on the target, returning predictions for the pion yield and energy deposition densities.

The yield per proton for pions-plus-kaons-plus-muons at 70 cm downstream from the central intersection of the beam with the target was predicted to be 0.715 (positive) and 0.636 (negative) for the momentum range 0.05< p <0.80 GeV/c,

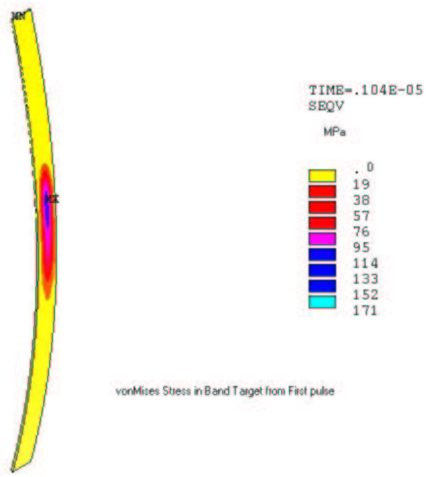

Figure 5: Predicted von Mises stress distribution for the "free edge" target band model at 1 microsecond after the arrival of the proton pulse. The maximum predicted von Mises stress at this time is 171 MPa.

and 0.304 (positive) and 0.288 (negative) for the kinetic energy range $32 < E_{kin} < 232$ MeV that approximates the capture acceptance of the entire cooling channel. Note that the material in the flanges of the I-beam was not included in the calculation; its inclusion might result in a small change in the predicted yield. For comparison, the predicted yield was 18% higher for the identical geometry but with the band material hypothetically changed from inconel to mercury.

Approximately 7% of the proton beam energy is deposited in the target as heat and the maximum instantaneous energy deposition from a single proton bunch is approximately 13 J/g, which corresponds to a temperature rise of 29 degrees centigrade. Detailed 3-dimensional maps of energy deposition densities were generated for input to the dynamic target stress calculations that are discussed in the following section.

9 Shock Heating Stresses

Probably the most critical issue faced in solid-target design scenarios for pion production at neutrino factories or muon colliders is the survivability and long-term structural integrity of solid targets in the face of repeated shock heating. To investigate this, finite element computer simulations of the shock heating stresses have been conducted using ANSYS, a commercial package that is widely used for stress and thermal calculations.

The target band geometry was discretised into a 3-dimensional mesh containing approximately 30 000 elements. This was as fine as the computing capacity and memory allowed and was considered adequate for the accurate modeling of shock wave propagation.

The dynamic stress analyses were preceded by a transient thermal analysis to generate temperature profiles using as input the 3-dimensional energy deposition profiles previously generated by MARS (see the preceding section). Dynamic stress calculations were then performed both for a “free edge” band, i.e., with no I-beam flanges, and with a “fixed edge” constraint where the edges of the band are constrained against displacement in both the radial and axial direction. The “fixed edge” model is considered likely to provide an improved approximation to the actual band with I-beam flanges without the extra computing capacity required to simulate the more complicated true geometry.

The von Mises stress (i.e. the deviation from the hydrostatic state of stress) was found to be initially zero but to develop and fluctuate over time as the directional stresses relax or are reflected from material boundaries. Figure 5 gives a snap-shot of the predicted von Mises stress distribution at 1 microsecond after the arrival of a proton pulse, figure 6 shows the time development of the predicted stress at the position of maximum stress and figure 7 shows the predicted target band deformations and von Mises stresses at 30 microseconds and 50 microseconds after the arrival of the beam pulse, for the “free edge” band model. The predicted 190 MPa peak value, in both time and position, for the von Mises stress from a single proton bunch is much less than the 740–1100 MPa yield strength for inconel 718 and is also well below its fatigue strength.

The calculations assumed a circumferentially continuous band. It remains to be done to check the level of von Mises stresses at the gaps between the eight welded band sections. It is noted that the BNL g-2 target was deliberately segmented longitudinally in order to reduce the beam stresses and that additional periodic slots in the webbing are under consideration [**?**] for thermal stress relief (and eddy current reduction) in rotating band targets for muon colliders, where the instantaneous proton bunch charges may be several times larger than considered here.

The ANSYS simulations conservatively assumed that the deposited energy is all converted to an instantaneous local temperature rise. Circumstantial evidence that this assumption may overestimate stress levels is provided by the operating parameters of existing targets. For example, the currently operating nickel target at the Fermilab antiproton source has absorbed peak energy depositions of up to 600 J/g over 2.4 microseconds, corresponding to an impressive 1100^oC temperature rise [13]. A more definitive confirmation of the survivability and safety margins for this target scenario should be provided by data from the ongoing BNL E951 targetry experiment [14], with planned stress tests for bunched 24 GeV proton beams incident on several types of targets, including inconel 718.

10 Conclusions

In summary, the inconel rotating band target design appears to be a promising back-up option to the base-line mercury jet target. The pion yield appears slightly lower than the mercury base-line. although this has yet to be fully optimized. The engineering design looks manageable and initial simulations of target stresses are encouraging.

Priorities for further evaluation of this target scenario include improved engineering designs of the components, optimization of the band geometry for pion yield and calibration of the target stress predictions to experimental targetry results from BNL E951 and elsewhere.

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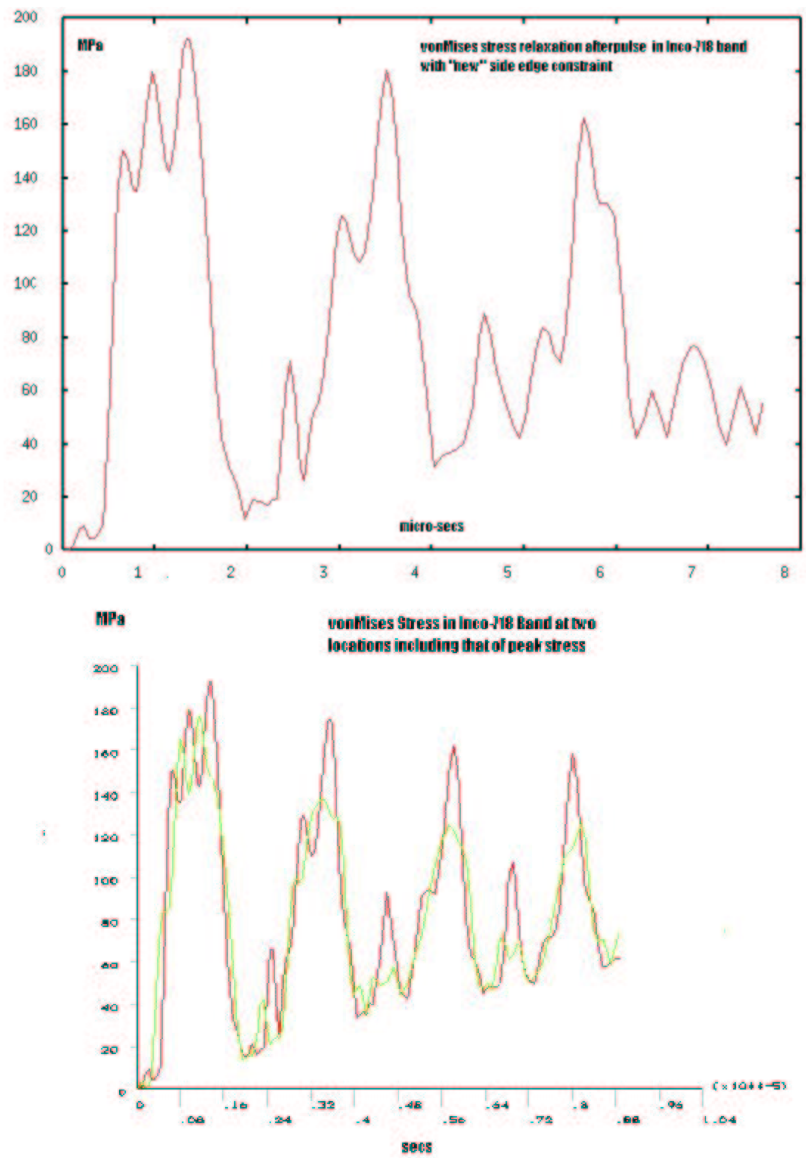

Figure 6: Predicted time dependence of von Mises stresses for the "fixed edge" (top) and "free edge" (bottom) target band models. The time origin corresponds to the arrival of the proton pulse. The stress values are shown for the position of maximum stress in both cases. Additionally, the stress in another location is shown as the light tracing for the free edge model.

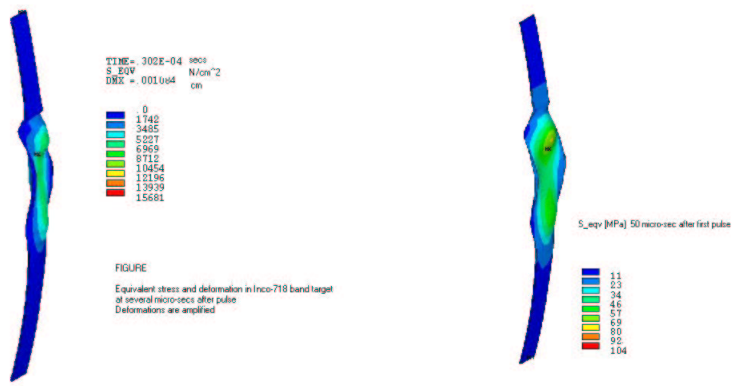

Figure 7: Predicted target band deformations, greatly exaggerated, and von Mises stresses at 30 microseconds (left) and 50 microseconds (right) after the arrival of the beam pulse, for the "free edge" band model. The maximum predicted von Mises stress is 157 MPa after 30 microseconds and 104 MPa after 50 microseconds.